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TEST OF DEPARTMENT OF ENERGY STRATEGIC PETROLEUM RESERVE CAVERN BRYAN MOUND 104

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Abstract

This document reports the certification test of Cavern Bryan Mound 104 conducted between September 19 and November 9, 1984. The test included pressurization with oil to near maximum test gradient, depressuring to maximum operating gradient, and doing nitrogen leak tests of the three cavern entry wells. Test results indicate nitrogen loss rates from the wells of 35 bbl/yr from 104A, 19 bbl/yr from 104B, and 0 bbl/yr from 104C. These nitrogen loss rates can reasonably be assumed to correspond to a total cavern oil loss rate of 5.4 bbl/yr, which is well within the DOE acceptance criterion of 100 bbl/yr of oil per cavern. The final phase of the nitrogen leak test was observed by a representative of the Texas Railroad Commission.

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INTRODUCTION

Regulations of the State of Texas Railroad Commission and the State of Louisiana Department of Conservation require inspections or tests to verify the mechanical integrity of wells into underground hydrocarbon storage caverns at least every five years. The Department of Energy (DOE) is vitally concerned with the integrity of not only the entry wells but with the entirety of all Strategic Petroleum Reserve (SPR) caverns in salt domes because of the potential for environmental damage and loss of a valuable resource. A plan (Ref. 1) was developed to meet the requirements of regulations of the two states and to provide a reasonable assurance of the integrity of SPR caverns, including entry wells. This plan includes (1) cavern pressurization to maximum test pressure and shut in to observe wellhead pressures for at least 1 day; (2) cavern depressurization to maximum operating pressure and shut in to observe wellhead pressure for at least 2 days, and (3) nitrogen leak tests of the cavern entry wells. The pressure time histories of (1) and (2), while providing no quantitative indication of cavern fluid loss rate, do provide a basis for comparison with other caverns having no known loss rates of significance. The well nitrogen leak tests (3) do provide an indication of fluid loss rates from the wells with an adequate resolution relative to the SPR oil loss rate goal of no more than 100 bbl/yr per cavern. Wells are generally expected to be the only source of cavern leaks because they are the only parts of caverns where integrity does not depend on the integrity of domal salt.

A test of the DOE/SPR oil storage cavern Bryan Mound 104 according to detailed procedures of Ref. 2, which are generally in accord with the plan of Ref. 1, was carried out between September 19 and November 9. 1984, by POSSI/Sandia. Maximum test pressure and maximum operating pressure respectively, corresponded to pressure gradients of 0.82 and 0.76 psi/ft to the shallowest casing seat. During the nitrogen well leak test at maximum operating pressure, the annuli of the 3 wells entering the cavern were filled with nitrogen to depths of 2050 feet, about 50 feet below the casing seats. The wellhead pressures and nitrogen-oil interface depths were monitored over a 23 day period to determine loss rates of nitrogen from the wells. The first 9 days of this period comprised a test to determine if there were problems with the procedures which should be corrected before performing an "official" test. When no such problems were noted, the Texas Railroad Commission was given 5 days notice that a nitrogen well leak test would be made.

A seven day test was then made with Mike Sanchez of the Texas Railroad Commission on site to witness logging of initial and final nitrogen-oil interface depths.

This report describes the test in detail and includes a documentation and analysis of test results.

CAVERN DESCRIPTION

Cavern Bryan Mound 104 has a volume of 11.6 x 10^6 bbls. It extends from depths of 2085 to 4180 feet below the Bradenhead flange, which is located near ground surface. Top of salt is more than 800 feet above the cavern roof.

Three wells cased with 13-3/8 inch casing enter the cavern. The wells were drilled between April and August 1979 (Ref. 3, 4, and 5) and initial leak tests of the wells were made between December 1979 and February 1980 (Ref. 6). Current configurations of the wells are as follow:

Well	Casing	Depth Below Bradenhead Flange (feet)
104A	Final cemented; 13-3/8; 54.5 lb/ft, K-55 to -	1629
	61 lb/ft, K-55 to -	1987
	Suspended; 10-3/4, 51 lb/ft, K-55 to -	3103
104B	Final cemented; 13-3/8; 54.5 lb/ft, K-55 to -	1629
	61 lb/ft, K-55 to -	2010
	Suspended; 10-3/4, 51 lb/ft, K-55 to -	4168
104C	Final cemented: 13-3/8; 54.5 lb/ft, K-55 to -	1664
	62 lb/ft, K-55 to -	1992
	Suspended; 8-5/8, 32 lb/ft, K-55 to -	4173

Cavern leaching was completed in March 1983 and the oil fill was completed in October 1983. Approximately 11.3 x 10^6 bbl of oil are currently stored in the cavern and the oil-brine interface depth was measured at 4054 to 4061 feet in the three wells during this test.

INSTRUMENTATION

Pressure

Wellhead pressures in the annulus and in the suspended casing of each of the 3 wells were measured by use of a Sperry Sun "Mr. Six" pressure recording system. A separate strain gage pressure probe at each pressure measuring point was connected to the Mr. Six unit. The Mr. Six unit sequentially digitized and recorded on paper tape the wellhead pressure and probe temperature for each individual probe at pre-selected time intervals. The Mr. Six unit also provided a digital input to a data recording system provided by Sandia, which consisted of a Hewlett Packard 9915 computer which sorted and stored data provided by Mr. Six onto a magnetic tape cassette.

Pressure data stored on the tape cassette were processed with a Hewlett Packard 85 computer.

In addition to the above described pressure recording system, commercial dial type pressure gages were installed on the annulus and suspended casing of each wellhead. Pressures from these gages were recorded during the test but are not reported herein.

Flow

During initial pressurization of the cavern by oil injection, oil volume injected was measured using an 8-inch Daniels turbine flowmeter located downstream of the site blanket oil pumps. Volume injected was recorded simultaneously with cavern pressure in order to define the oil-filled cavern elasticity.

Nitrogen Weight

In preparation for nitrogen well leak tests, nitrogen injected into the well annuli was weighed by use of a weighing system developed and operated by Waukesha Pearce. The system includes a liquid nitrogen filled tank suspended from an overhead frame by use of a load cell. Liquid nitrogen flows from the tank through flexible hoses to a vaporizer and then a heater before it is injected into the well.

During nitrogen injection into the lower cased part of the well and the open hole below the casing seat, weight of nitrogen injected is recorded simultaneously with pressure and nitrogen-oil interface depth. Data are recorded at depth intervals as small as 10 feet in the cased part of the well and at depth intervals of about 5 feet in the open hole.

The purpose of the nitrogen weight measurements is to indicate annulus volume below the casing seat so that measured interface movements during the test can be related to changes of nitrogen volume. Weight measurements in the cased parts of the wells where volumes are known, are used to establish a calibration factor for the weighing system. It has been determined previously that volumes calculated for the cased portion of wells from nitrogen weight measurements deviate significantly from known volumes. It is suspected that nitrogen tank weights indicated by the load cell are affected by the flow of liquid nitrogen through the flexible lines from the tank to the vaporizer, and possibly other factors.

Interface Death

Nitrogen-oil interface depths in the annuli were measured by Microgage using their standard wire line equipment including a standard density logging tool with a double strength neutron source.

Nitrogen Volume

During the nitrogen test it was discovered that nitrogen was leaking from the annulus of well 104B into the suspended 10-3/4 inch string. In order to determine the net loss of nitrogen from the well, it was necessary to determine the amount of nitrogen accumulated in the hanging string during the test period. This was accomplished by use of a measuring system developed by Sandia, which is shown schematically in Fig. 1. The high pressure tank was filled with water and the top of the tank was connected to the suspended string at the wellhead. Water was bled from the bottom of the tank into an open holding tank. The water bled from the bottom of the tank was replaced by nitrogen from the suspended string entering the top of the tank. Nitrogen from the well passed through a sight gage before it entered the tank so that the arrival of liquid, and consequently, the end of gas, could be observed. The high pressure tank was equipped with a volume calibrated sight glass for determining gas volume bled from the well.

TEST DESCRIPTION

Cavern Pressurization with Oil

The cavern was initially pressurized from near atmospheric wellhead oil pressure to 820 psig during the period September 19-21, 1984. Oil was used instead of brine for pressurization, because of problems with brine surface piping to the pad, and was injected into the annulus of well 104C. It was injected by use of one of the blanket oil pumps with a Daniels turbine flow meter permanently installed in downstream piping. Initial pressurization was limited to 820 psig (a test gradient of 0.78 psi/ft).

After the cavern was pressurized, an oil leak was found at the wellhead of well 104A and brine leaks were found at the wellheads of wells 104B and 104C. Repair of the oil leak required cavern depressurization to atmospheric wellhead oil pressure. Cavern depressurization was started on September 22. Measured cavern wellhead pressures starting September 22 are shown in Figs. 2a and 2b.

Wellhead leaks were repaired and cavern pressurization was started a second time on September 25. The initial portion of this second cavern pressurization to about 320 psig was accomplished by connecting oil lines from caverns 102 and 103 to cavern 104, and allowing oil to flow into cavern 104 until the oil pressures in the three caverns equalized. Pressurization was continued to a wellhead oil pressure of about 780 psig using the site oil injection pumps with only a fraction of their discharge going into cavern 104. Pressurization was then continued by use of the blanket oil pump. A pressure of 860 psig (maximum test pressure) was reached at 2400 hours on September 27 and the cavern was shut in. Wellhead pressures during this second cavern pressurization are shown from 80 to 144 hours on Figs. 2a and 2b.

Following this pressurization, the cavern was shut in for 2 days. Cavern pressure was then reduced to a wellhead oil pressure of 770 psig (maximum operating pressure) for an additional two days. Wellhead pressures during these two shut in periods are shown from 144 to 255 hours on Figs. 2a and 2b.

On October 2, after wellhead oil pressure had been at 770 psig for about 2 days, an oil leak was discovered around the stem of a 6 inch gate valve on well 104A. While the oil leak was small enough to be of minor importance, it was felt that the nitrogen leak at this point at considerably higher pressures during a later part of the test could be quite important. The cavern pressure was again reduced to zero wellhead oil pressure to make a repair. This depressurization was begun at 15:45 on October 2 (256 hours on Figs. 2a and 2b).

Repressurization and Nitrogen Injection

Following repair of the oil leak around the valve stem on well 104A, the cavern was repressured to maximum operating pressure October 10 by bleeding oil from caverns 102 and 103 and then using a fraction of the flow from the site oil injection pumps. Nitrogen was then injected into the annuli of each of the three cavern 104 wells, starting on October 15, to a depth of 2050 feet. Wellhead pressures during this repressurization, nitrogen injection, and a subsequent stabilization period are shown in Fig. 3.

Nitrogen was injected into well 104A until the wellhead nitrogen pressure reached 1265 psig at 159 hours. During this injection it had not been possible to locate the nitrogen-oil interface with the interface logging tool due to tool malfunction. Since interface depth together with weight of nitrogen injected is required for defining hole volume, nitrogen injection was stopped until another logging tool could be obtained. Nitrogen remaining in the weighing tank was injected into the annulus of well 104C to achieve a wellhead pressure of 1160 psig without attempting an interface measurement.

At 180 hours, nitrogen was injected into the annulus of well 104B until the wellhead pressure increased to 1238 psig with no attempt at interface measurements. Injection into well 104A was started again at 185 hours with the Microgage TIP (Temperature-Interface-Pressure) logging tool in the well for interface measurements. This tool also malfunctioned and nitrogen injection was again stopped. Subsequently, interface depths were satisfactorily located using a standard interface logging tool with a double strength neutron source. Nitrogen weight measurements together with interface depths were obtained while setting interface depths of 2050 feet in wells 104A, 104C, and 104B, at times between 202 and 228 hours. Final wellhead nitrogen pressures were 1405 psig.

Pressures in the suspended strings of the three wells are also shown in Fig. 3. In well 104A, the bottom of the suspended string is well above the oil brine interface. The string is therefore oil filled and the wellhead pressure is an oil pressure. The suspended strings of wells 104B and 104C are brine filled and wellhead pressures measured are brine pressures. The brine pressure in well 104B was significantly higher than that in well 104C and the difference increased with time. This was due to nitrogen leaking from the annulus into the suspended string of well 104B. At 224 to 228 hours, the nitrogen cap was bled from well 104B and this reduced the brine pressure about 30 psi.

Nitrogen weight measurements were obtained at frequent interface depths in the lower cased portions of the well and at about 5 foot intervals below the cased portions of the wells. The purpose of the weight measurements was to allow calculation of incremental volumes in the open holes so that interface movements could be related to nitrogen volume change during the test. The calculation procedure used is described in Appendix A.

Nitrogen Leak Tests

The time during which the cavern was shut in with the three well annuli filled with nitrogen to depths of about 2050 feet covered about 23 days broken down approximately as follows; (1) 2 days for the nitrogen temperature to stabilize before measuring reference nitrogen-oil interface depths: (2) 7 days for the first test period; (3) 6 days waiting time after giving the Texas Railroad Commission notification that a test would be made; (4) a second 7 day test period with a representative of the Texas Railroad Commission on site to observe initial and final interface depth measurements. Wellhead annulus and string pressures measured during the entire shut in period, starting before the end of the data of Fig. 3 are presented in Fig. 4.

TEST RESULTS

Cavern Elasticity

The pressure/volume/time data obtained during the initial pressurization are presented in Figs. 5a to 5c. Fig. 5a is a graph of wellhead oil pressure in the annulus of well 104A versus time and indicates a mean pressurization rate determined from a linear regression of 13.4 psi/hr. Fig. 5b is a graph of injected oil volume versus time and indicates a mean injection rate determined from a linear regression of 846 bbl/hr. Fig. 5c is a graph of injected oil volume versus wellhead oil pressure and indicates a total cavern elasticity of 64.3 bbl/psi. For an assumed 11.3 x 10^6 bbl of oil in the cavern with an elasticity of 4.5 x 10^{-6} bbl/bbl-psi and an assumed 0.3 x 10^6 bbl of brine in the cavern with an elasticity of

2.25 x 10^{-6} bbl/bbl-psi, the elasticity of cavern fluids would be 51.5 bbl/psi. This indicates 12.8 bbl/psi is due to salt elasticity.

Cavern Shut In at Maximum Test Pressure

Cavern pressures during shut in at maximum test pressure are shown on expanded scale plots of Fig. 6. Linear regressions of these data indicate pressure decay rates of 1.3 to 3.5 psi/day. Deviations of the data from linear variations with time generally indicate the decay rates are decreasing slightly with time, a trend generally expected following cavern pressurization.

Cavern Shut In at Maximum Operating Pressure

Cavern pressures during shut in at maximum operating pressure following depressurization from maximum test pressure are shown on expanded scale plots of Fig. 7. Linear regressions of these data indicate pressure increase rates of 0.1 to 2.6 psi/day. Deviations of the data from linear variations with time generally indicate the pressure increase rates are decreasing slightly with time, a trend generally expected following cavern depressurization and shut in.

Borehole Caliper from Measurements During Nitrogen Injection

Calculated nitrogen column cross-sectional areas for wells 104A, 104B, and 104C are shown on the graphs of Figs. 8, 9, and 10, respectively. Included in the figures are measured values of interface depth, wellhead nitrogen pressure, and incremental weights of nitrogen injected between interface depths.

Two graphs are presented on each of Figs. 8 to 10. The top graphs show calculated nitrogen column cross-sectional areas in the cased parts of the wells and the lower graphs show calculated cross-sectional areas in the open holes below the casing seats. The gross calculated cross-sectional area in the cased part of the wells, upper graphs, is equal to that of the annulus between the last cemented casing and the suspended string. This correct value of gross calculated area was forced by adjusting the scale factor for the nitrogen weighing system to values between 0.90 and 1.00. The readings from the weight measuring technique are subject to a scaling influence due to nitrogen flow, and it is reasoned that if such a scaling is present during injection into the cased part of the well, it is almost certainly present in the open hole.

The cross-sectional areas in the open holes, lower graphs of Figs. 8 to 10, indicate considerable variation with depth in each well, and there are important differences between the three wells. Random variations with depth in each well, while quite sizable, are expected in that a one foot error in interface depth, when measurements are at five foot intervals, would result in a 20 percent error in a calculated cross-sectional area. The faired curves of cross-sectional area are used for calculating nitrogen volume change with interface depth change.

Nitrogen Leak Tests

With the exception of the suspended string of well 104B, all measurements indicated a continuous increase in cavern pressure at a rate of 0.041 ± 0.012 psi/hr. during the entire period, Fig. 4. The pressure in the suspended string of well 104B increased at a more rapid rate due to leakage of nitrogen from the annulus into the suspended string. This leakage into the suspended string, although lost from the annulus, was not lost from the well. To properly account for nitrogen initially injected into the annulus, it was necessary to measure the nitrogen accumulated in the string during the test periods. All nitrogen was bled from the string at the beginning of the first 7 day test period and was then bled and measured at the end of the period; similarly for the second 7 day test period. Results of accumulated nitrogen volume measurements at the end of the two test periods are in Table I. The nitrogen volumes were then adjusted to volumes at the initial average pressure of nitrogen in the annulus, and corresponding annual accumulation rates were calculated.

Results of oil-nitrogen interface depth measurements are summarized in Table II. Also included in Table II are calculated nitrogen volume loss rates. Nitrogen volume loss rates are calculated by use of the following equation which was derived in Ref. 2 as Eq. (4).

$$\Delta V_{id} \approx V_o \left[- \frac{\Delta P}{P_o} - \frac{\Delta V}{V_o} \right]$$

ΔV_{id}	volume lost, measured at initial nitrogen density in well
V_o	initial total volume of nitrogen in well
P_o	initial nitrogen pressure at wellhead
ΔP	change in wellhead pressure during test period
ΔV	change in nitrogen volume during test period

Overlays of sequential interface logs were used to determine interface movement during the test periods. In these overlays, the density signals on the logs corresponding to the casing seats were aligned. This technique should slightly improve the accuracy of interface movement determined from the logs, and the results are included in Table II. The changes in nitrogen volume during the test periods are equal to the products of interface movements thus determined and borehole volume per foot at the interface depth indicated by Figures 8 to 10.

The nitrogen loss rates calculated are included in Table II and vary from -31 to +101 bbls/yr. The negative loss rates calculated are, of course, not possible, and are believed to result from inaccurate measurements, particularly those of interface depth. For example, a one foot error in interface depth movement during a one week period, which is less than the expected accuracy, would correspond to an error in loss rate of 67 bbl/yr for well 104A, 33 bbl/yr for well 104B, and 26 bbl/yr for well 104C.

It is believed that the best estimates of nitrogen loss rates for the complete test, based on the test measurements are 35 bbl/yr for well 104A, 19 bbl/yr for well 104B and 0 bbl/yr for well 104C. These estimates are based on results for the entire 20-21 days after nitrogen temperature stabilization, rather than the individual 6 to 7 day test periods. It has been proposed in Ref. 7 that it is reasonable to assume a value of 10 for the ratio of volumetric nitrogen to oil leak rates. With this assumption, the measured nitrogen loss rates correspond to a total cavern-oil loss rate of 5.4 bbl/yr.

CONCLUSIONS

The test results indicate no reason to question the integrity of cavern Bryan Mound 104. During shut in following pressurization to maximum test pressure, cavern pressures decreased slightly with time, but at a rate decreasing with time. This behavior is typically observed in caverns with no known significant leaks. During shut in following depressurization from maximum test pressure to maximum operating pressure, cavern pressures increased slightly with time, but at a rate decreasing with time. This behavior is also typically observed in caverns with no known significant leaks.

Nitrogen leak tests were made of the three wells entering the cavern to depths below the last cemented casing, the parts of the cavern from which leaks are most likely to OCCUL. The best estimate of well leak rates from these tests are 0, 19, and 35 bbl/yr of nitrogen from wells 104C, 104B and 104A respectively. These nitrogen leak rates can be reasonably assumed to correspond to a total cavern oil loss rate of 5.4 bbl/yr, and are thus insignificant in comparison to the DOE criterion of 100 bbl/yr of oil for a cavern.

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6. Goin, Kennith L., "Analysis and Leak Tests of Wells for Solution Mined Caverns at the Bryan Mound DOE-SPR Storage Site," SAND81-0978, April 1981.

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Table I. Measurements of Nitrogen Accumulated in the Suspended String of Well 104B

Accumulation between 10/20 and 10/27 (7.128 days, Table II.)

Date of Measurement	Time	Volume bbls	Pressure at Which Volume Measured-PSIG	Volume (bbls) at Initial Average Column Pressure of:	Total Volume bbls
				(1470 PSIA)	
10-26-84	13:45	1.071	174.3	1377	
	14:35	1.076	169.6	: 1349	
	15:25	1.071	164.7	.1307	
	16:03	1.071	160.0	.1273	
	16:57	1.071	154.8	. 1235	
	17:40	1.076	151.3	. 1215	
	18:10	.424	151.4	.0479	
10-27-84	13:15	.643	153.4	.0735	
	14:10	.171	152.6	.0195	
					.9165
				Rate 47 bbls/yr	

Accumulation between 11/2 and 11/9 (6.972 days, Table II.)

Date of Measurement	Time	Volume bbls	Pressure at Which Volume Measured-PSIG	Volume (bbls) at Initial Average Column Pressure of:	Total Volume bbls
				(1482 PSIA)	
11-8-84	13:21	1.071	172.4	.1363	
	14:00	1.083	167.2	.1340	
	15:10	1.071	164.8	. 1308	
	15:30	.286	164.6	.0349	
11-9-84	11:53	.690	165.9	.0848	
					.5208
				Rate 27 bbls/yr	

Table II. Summary of Nitrogen-Oil Interface Results and Nitrogen Loss Rate Calculations

WELL	DATE	TIME	HOURS FROM 00:00 10-9-84	N_2 PRESS PSIG	N_2 OIL IF DEPTH FROM LOG FT	IF MOVEMENT FROM OVERLAY OF LOGS - FT	(1) HOLE VOL AT IF DEPTH FT^3/FT	TIME INTERVAL DAYS	(2) N_2 LOSS RATE BBLS/YR
104A	10/17	1213	204.22	1405.8	2050				
	10/19	1234	252.57	1408.5	2050				
	10/26	1211	420.18	1413.1	2050	0.5 UP	7.25	6.984	9
	11/02	1011	586.18	1420.3	2048	0.5 UP	7.25	6.917	-5
	11/09	1027	754.45	1426.7	2047	2.0 UP	7.25	7.011	101
104B	10/18	1157	227.95	1405.9	2050				
	10/20	1200	276.00	1407.3	2049				
	10/27	1505	447.08	1412.4	2047	3.0 UP	3.60	7.128	79 (3)
	11/2	1333	589.55	1418.8	2044	2.0 UP	3.55	5.936	49 (4)
	11/9	1253	756.88	1425.1	2042	2.0 UP	3.50	6.972	41 (5)
104C	10/17	1837	210.62	1405.2	2050				
	10/20	1050	274.83	1406.8	2050				
	10/27	1318	445.30	1413.0	2048	1.5 UP	2.85	7.103	-4
	11/2	1219	588.32	1418.6	2048	0.5 UP	2.85	5.959	-31
	11/9	1153	755.88	1425.7	2047	1.5 UP	2.85	6.982	-10

(1) From measured weight of nitrogen injected, see Figures 8, 9 and 10.
(2) Calculated by Eq. (4) of Ref. 2, - Nitrogen volume changes for calculations based on interface movements determined from overlay of sequential logs - Nitrogen volume loss rate calculated at pressure at time of initial interface measurement.
(3) Includes measured loss rate to hanging string of 47 bbls/yr.
(4) A loss to hanging string was present but rate was not measured.
(5) Includes measured loss rate to hanging string of 27 bbls/yr.

APPENDIX A.
CALCULATION OF OPEN HOLE VOLUMES FROM MEASURED WEIGHTS OF NITROGEN INJECTED

Appendix A.

Calculation of Open Hole Volumes from Measured Weights of Nitrogen Injected

In columns of fluids, the pressures at depth are dependent on the pressure at the top of the column and the weight of fluid from the top to the depth of interest. Although column weights for gases are generally not large compared to liquids, they are significant when column heights are 2000 feet or more, as in many SPR wells. An approximation for the pressure at depth in a column of gas is defined as follows:

$$P = P_s \, k^Y \qquad \text{(A1)}$$

where

$$k = \left[1 + \frac{1}{ZRT}\right]$$

- P absolute pressure at depth, psfa
- P_s absolute pressure at top of column, psfa
- Y depth in column at which pressure is defined, ft
- R gas constant 55.159 ft/°R for nitrogen
- T temperature of gas in column, °R, assumed constant over height of column
- z compressibility of gas in column, assumed constant over height of column

The compressibility of nitrogen is a function of both pressure and temperature and is calculated for the assumed average nitrogen temperature and the approximate average nitrogen pressure in the column. At 100 atmospheres pressure and 100°F temperature, which approximate conditions of the subject test, the value of compressibility, Z, equals 1.014 and the value of k in Eq. (Al) is 1.00003195.

The equation of state for a gas defines the following relation.

$$W = \frac{PV}{ZRT} \tag{A2}$$

where

W weight, lbs

P pressure, psf a

V volume, ft^3

In a gas column with ZRT assumed constant, eq. (AZ) leads to:

$$dW = \frac{d(PV)}{ZRT} = \frac{PdV}{ZRT} \tag{A3}$$

Letting A equal the local cross-sectional area of the gas column in the well at depth, y:

$$dV = Ady \tag{A4}$$

Combining Eqs. (Al), (A3) and (A4) yields

$$dW = \frac{P_s k^y}{ZBT} A \ dy \tag{A5}$$

Integration of Eq. (A5) from the surface to any depth, y, in the nitrogen column yields the weight of nitrogen to that depth;

$$W = \int_0^Y dW = \frac{P_s}{ZRT} \int_0^Y Ak^y dy \tag{A6}$$

Typically nitrogen weight measurements for use in borehole size calculations are begun in the lower cased part of the well. Cross-sectional area of the nitrogen column from the surface to the depth for beginning the calculations, yl, is a known constant, A_1, equal to the area between the inside surface of the cemented casing and the outside surface of the suspended string. Integration of Eq. (A6) from the top of the nitrogen column to depth yl using a constant nitrogen column cross-sectional area of Al yields

$$W_{1,1} = \left(\frac{P_s}{ZRT}\right)_1 A_1 \left[\frac{k_1^{y_1} - 1}{\ln k_1}\right] \tag{A7}$$

where

$W_{1,1}$ indicate6 weight to the first interface depth (first subscript) at the time of the first interface measurement (second subscript)

As nitrogen is added to move the interface depth to the second value, y_2 and the surface pressure is increased to $P_{s,2}$, the weight in the column to the 1st interface depth is increased to

$$W_{1,2} = \left(\frac{P_s}{ZRT}\right)_2 A_1 \left[\frac{k_2^{y_1} - 1}{\ln k_2}\right] \tag{A8}$$

At the time of the second interface measurement, the weight of nitrogen in the column between the first and second interface depths is, from Eq. (A5);

$$W_{1-2,\ 2} = \left(\frac{P_s}{ZRT}\right)_2 A_2(Y_2 - Y_1) \left[\frac{k_2^{y2} + k_2^{Y_1}}{2}\right] \tag{A9}$$

The total weight of nitrogen in the column at the time of the second interface depth is the sum of Eqs. **(A8)** and **(A9).**

$$W_{2,\,2} = \left(\frac{P_s}{ZRT}\right)_2 \left\{ A_1 \left[\frac{k_2^{\,y_1} - 1}{\ln k_2}\right] + A_2(y_2 - y_1) \left[\frac{k_2^{\,y_2} + k_2^{\,y_1}}{2}\right]\right\} \qquad \text{(A10)}$$

At subsequent interface depths, the total weight in the column is

$$W_{n,\,n} = \left(\frac{P_s}{ZRT}\right)_n \left\{ A_1 \left[\frac{k_n^{\,y_1} - 1}{\ln k_n}\right] + \sum_{i=2}^{i=n} A_i(y_i - y_{i-1}) \left[\frac{k_n^{\,y_i} + k_n^{\,y_{i-1}}}{2}\right]\right\} \qquad \text{(A11)}$$

Similarly, with $m = n - 1$

$$W_{m,\,m} = \left(\frac{P_s}{ZRT}\right)_m \left\{ A_1 \left[\frac{k_m^{\,y_1} - 1}{\ln k_m}\right] + \sum_{i=2}^{i=m} A_i(y_i - y_{i-1}) \left[\frac{k_m^{\,y_i} + k_m^{\,y_{i-1}}}{2}\right]\right\} \qquad \text{(A12)}$$

The weight of nitrogen added to move the interface from depth y_m to depth y_n is the difference between (All) and (A12).

$$\Delta W_{m-n} = W_{n,n} - W_{m,m} \qquad \text{(A13)}$$

With n = 2 and the measured weight, ΔW_{1-2}, Eq. (13) can be solved for A_2, the average cross-sectional area between interface depths yl and y_2. Subsequently, with n = 3, the measured weight, ΔW_{2-3}, and the above calculated value of A_2, Eq. (A13) can be solved for A_3, etc.

The above described procedure is used to calculate nitrogen column cross-sections from the first to last measured interface depths. The first several cross-sections calculated are in the cased part of the well, where the column cross-sectional area is constant and known (assuming no effect of collars on the suspended string). It has been found in many cases that areas calculated in the cased part of the well deviate significantly from known cross-sectional areas. Since there is a probability of some scaling error in the measured weights, a scale factor was determined by an iterative process that resulted in the average calculated cross-sectional area in the cased part of the well being equal to the known value. This scale factor should also be applicable to measurements in the open hole and should therefore result in the most reasonable values of calculated borehole cross-section below the casing seat.

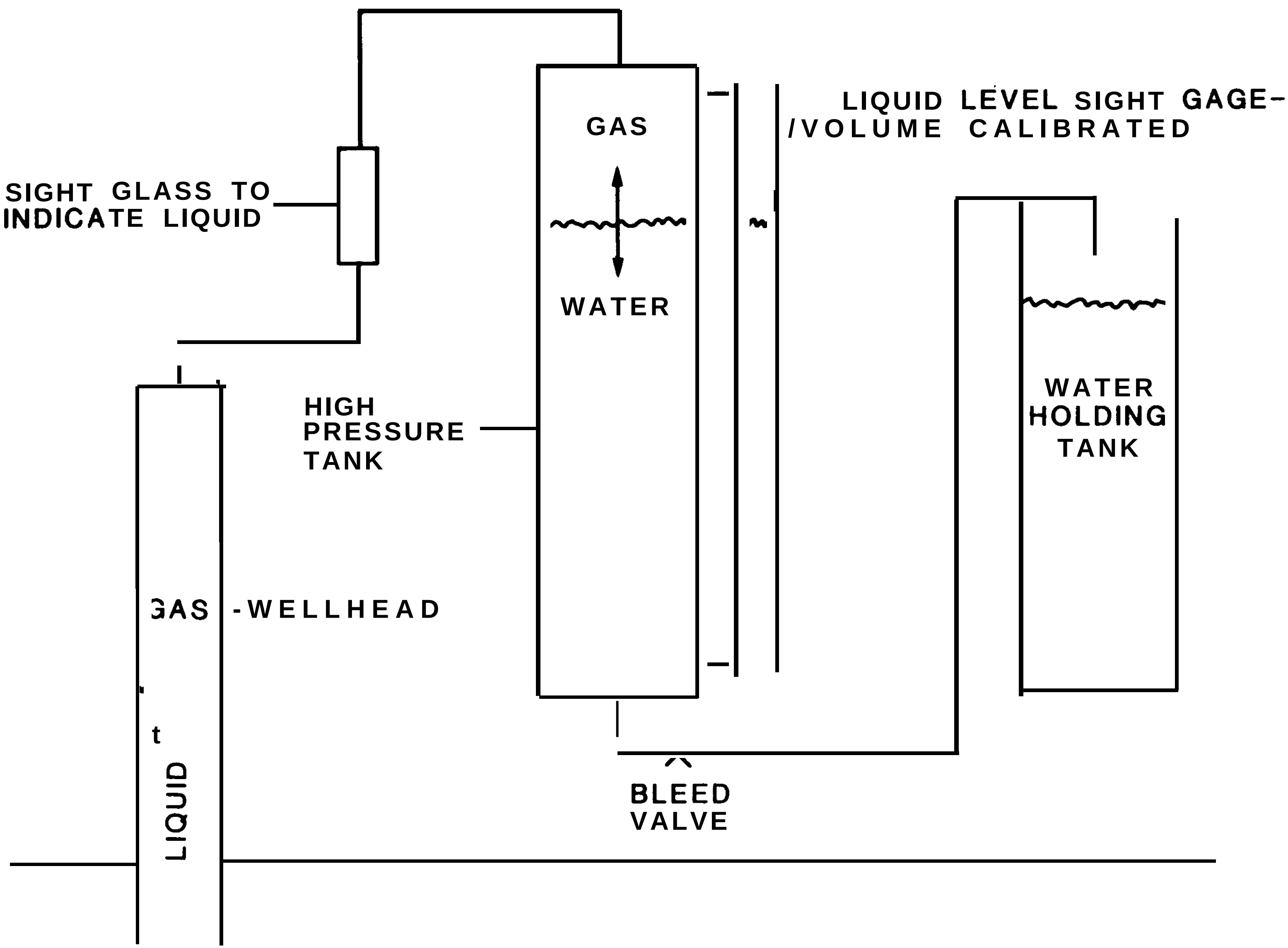
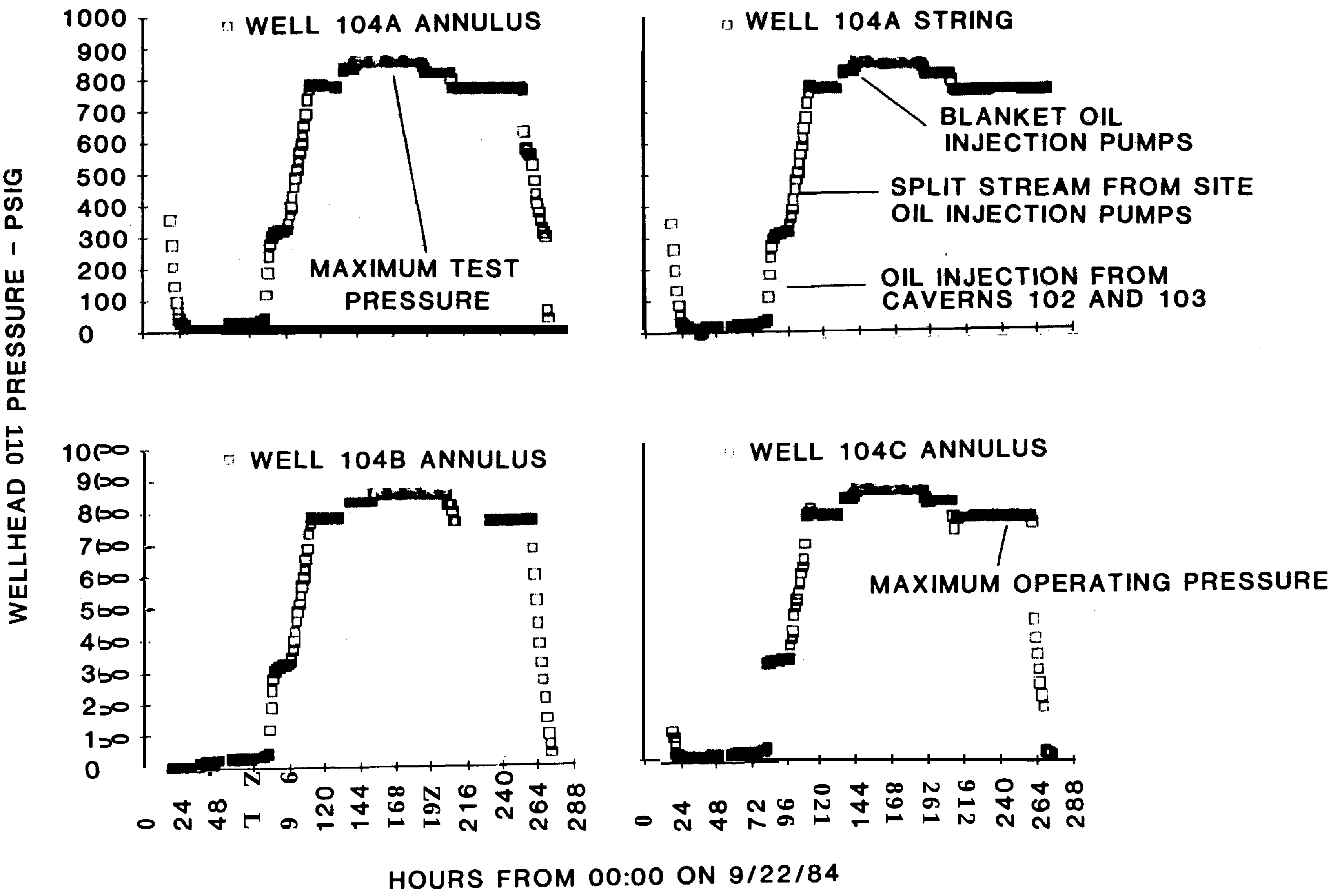
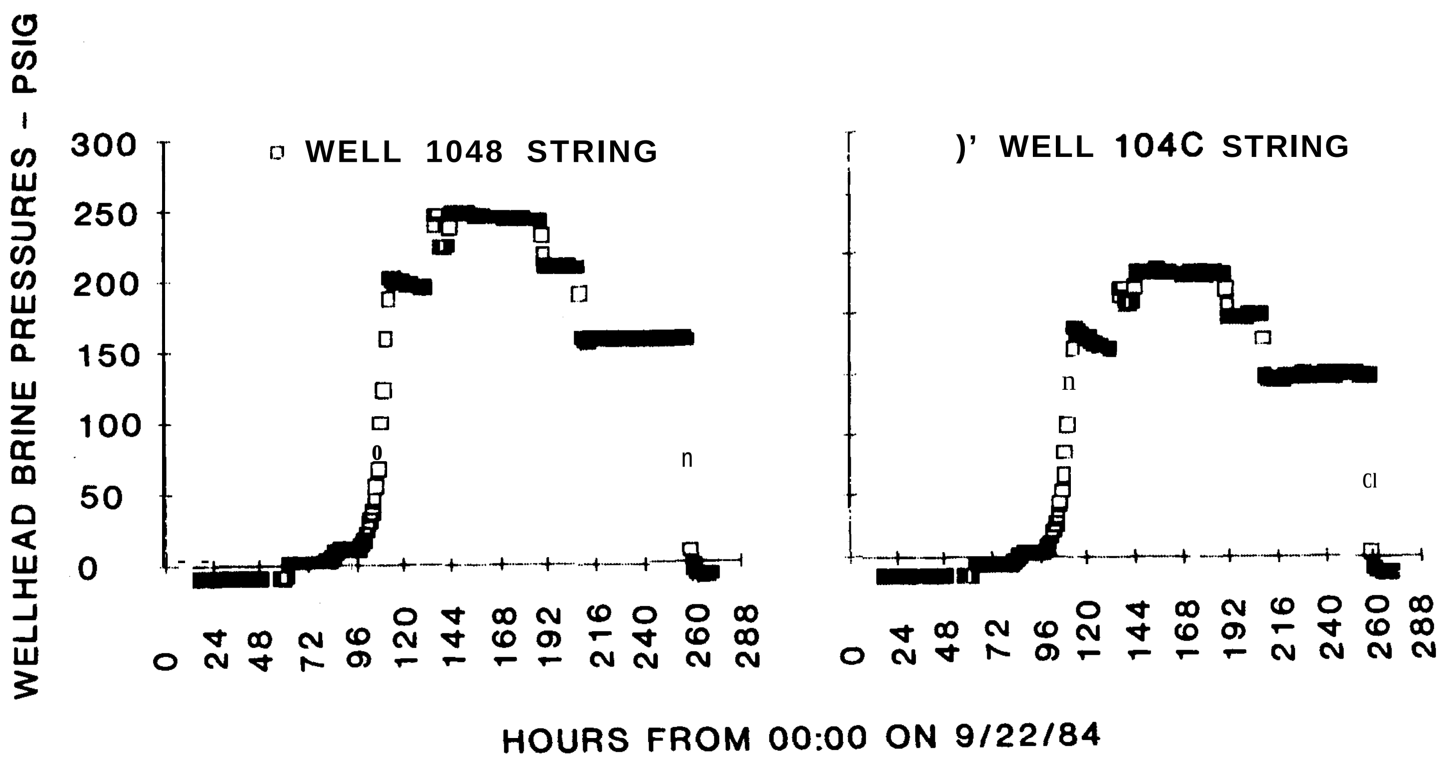


FIGURE 1. -SCHEMATIC OF SYSTEM FOR MEASURING VOLUME OF GAS ACCUMULATION



A. OIL PRESSURES

FIGURE 2. - WELLHEAD PRESSURES



B. BRINE PRESSURES

FIGURE 2. -CONCLUDED

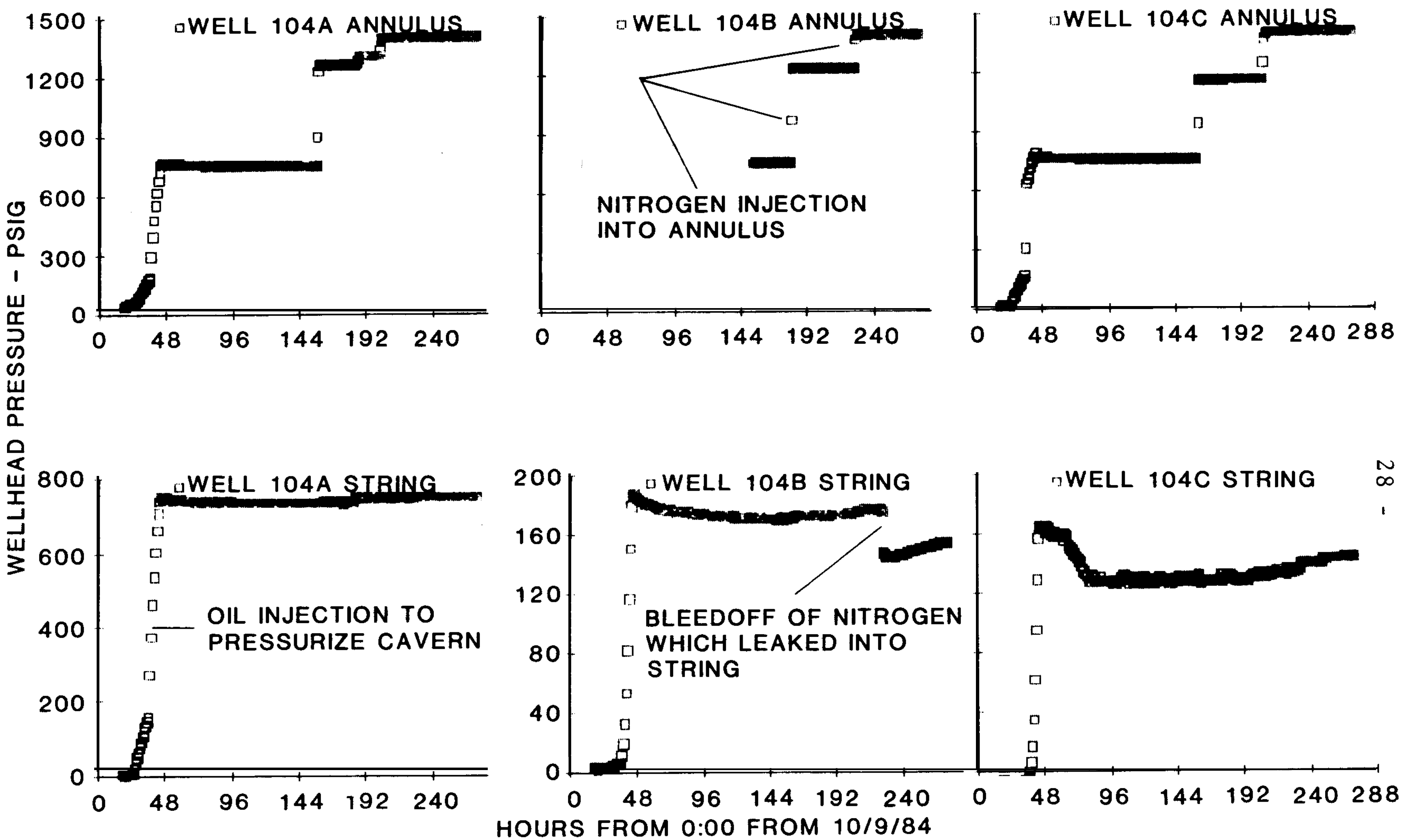


FIGURE 3. -CAVERN PRESSURIZATION, NITROGEN INJECTION, AND NITROGEN
TEMPERATURE STABILIZATION PERIOD

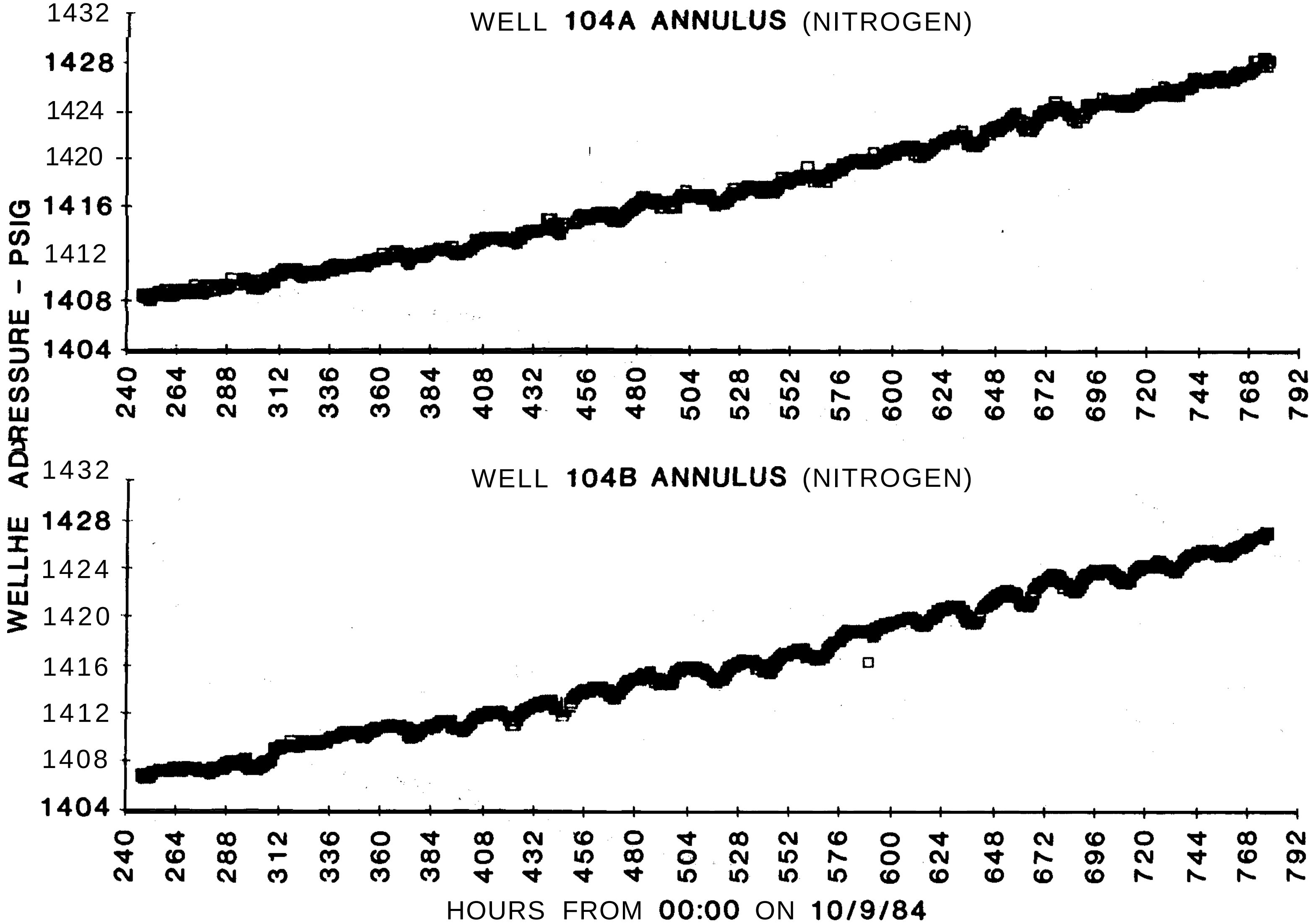


FIGURE 4. - **WELLHEAD** PRESSURES DURING THE TIME THE CAVERN WAS SHUT IN WITH NITROGEN IN THE WELL **ANNULI**

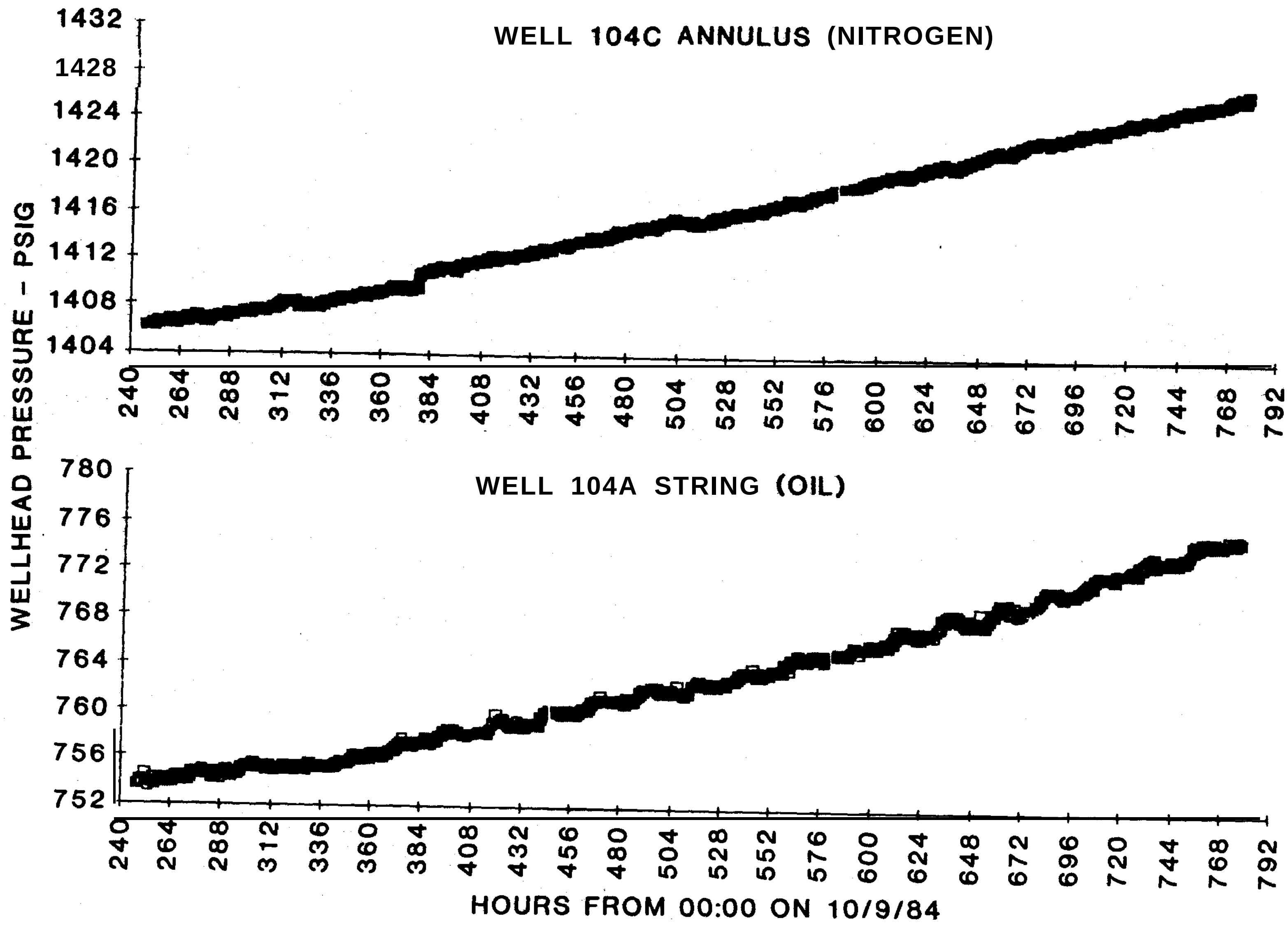


FIGURE 4. - CONTINUED

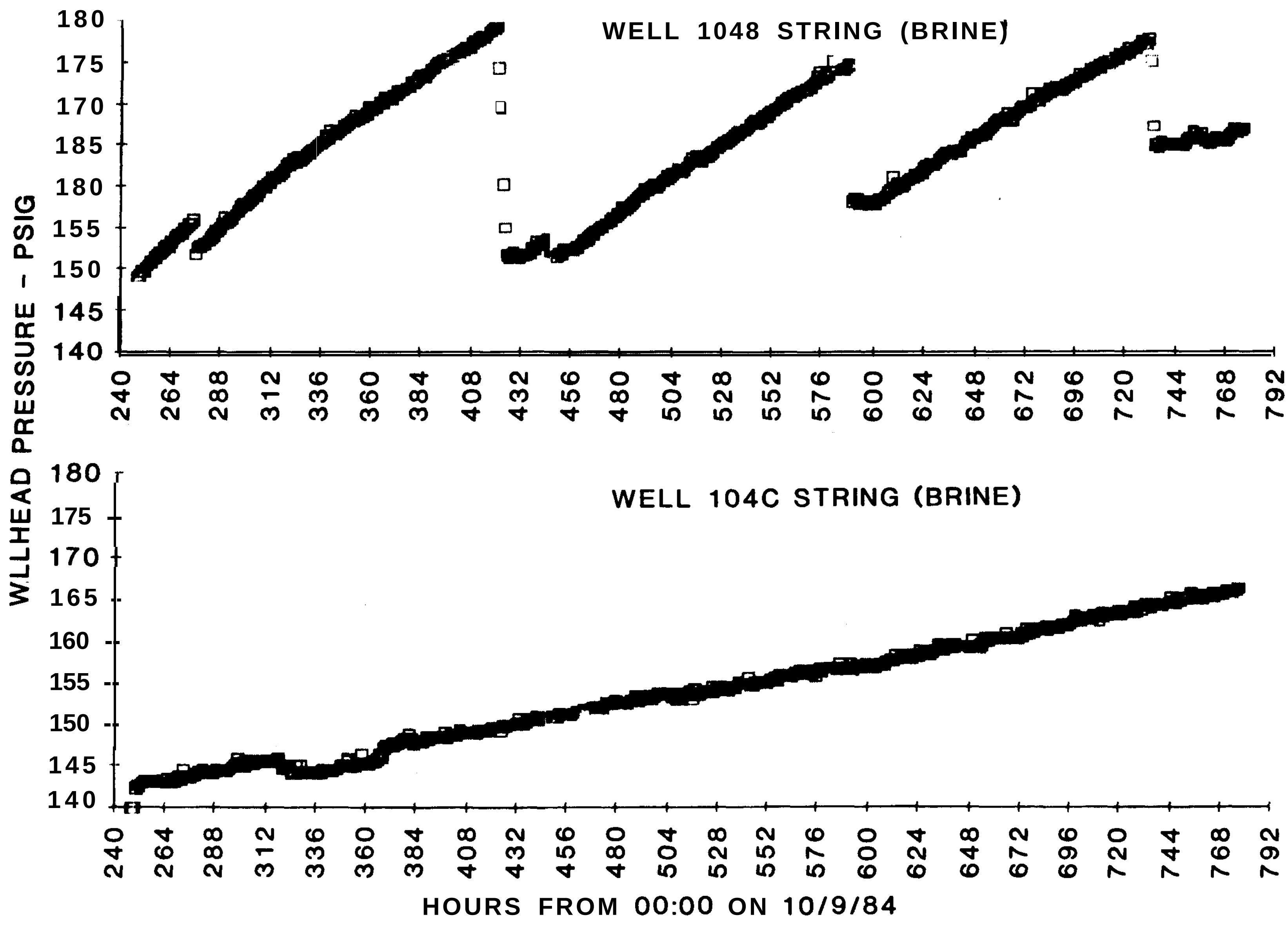
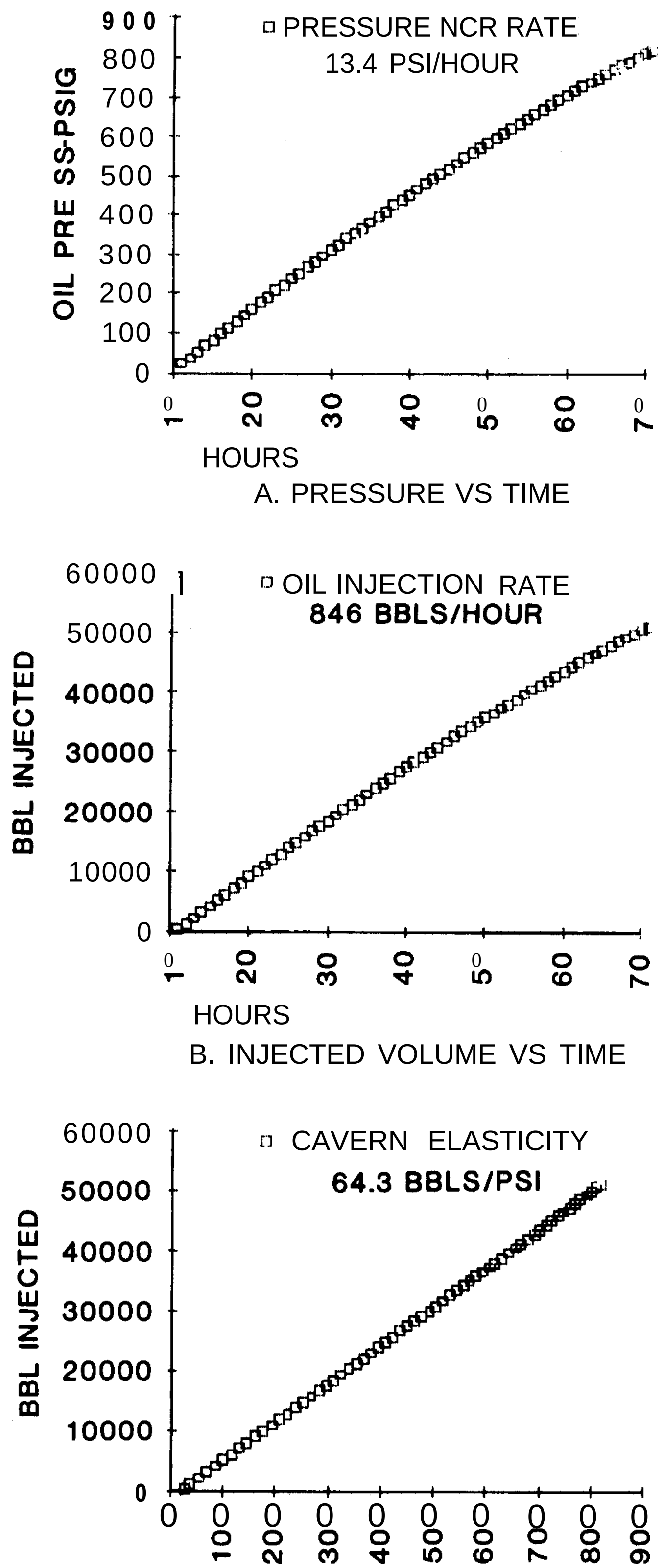


FIGURE 4. – CONCLUDED

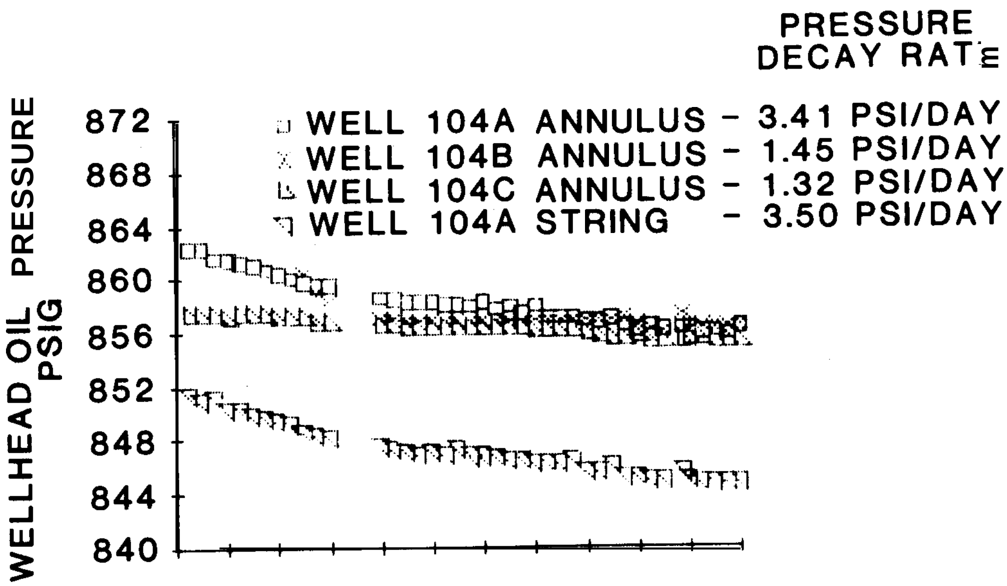


A. PRESSURE VS TIME

B. INJECTED VOLUME VS TIME

C. INJECTED VOLUME VS PRESSURE

FIGURE 5. - CAVERN PRESSURIZATION RESULTS.



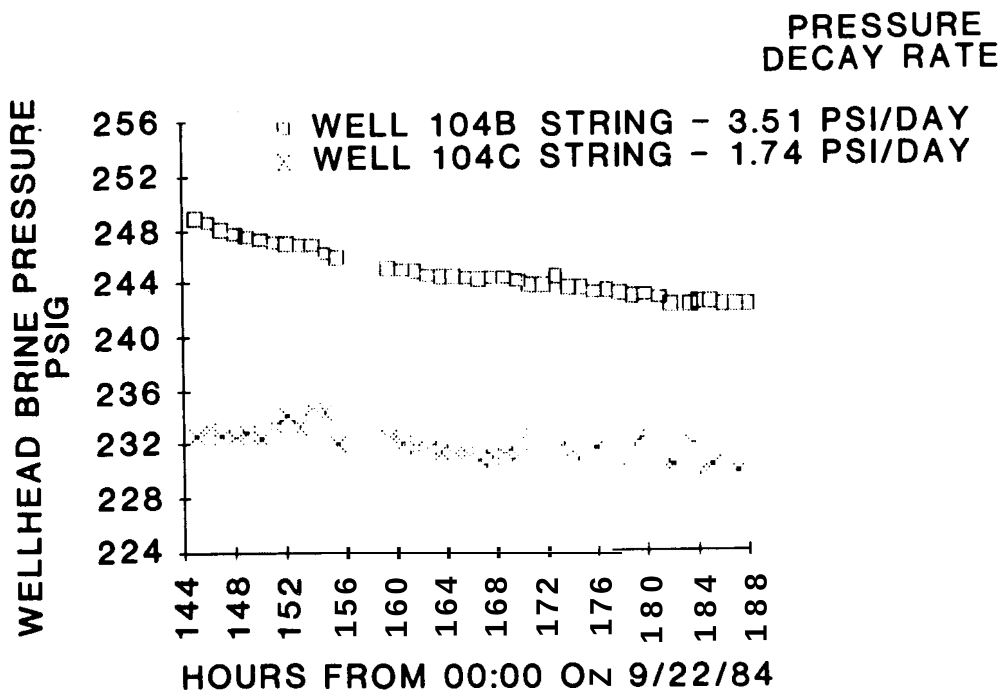


FIGURE 6. - EXPANDED SCALE PLOTS OF PRESSURE FOLLOWING SHUT IN AT MAXIMUM TEST PRESSURE.

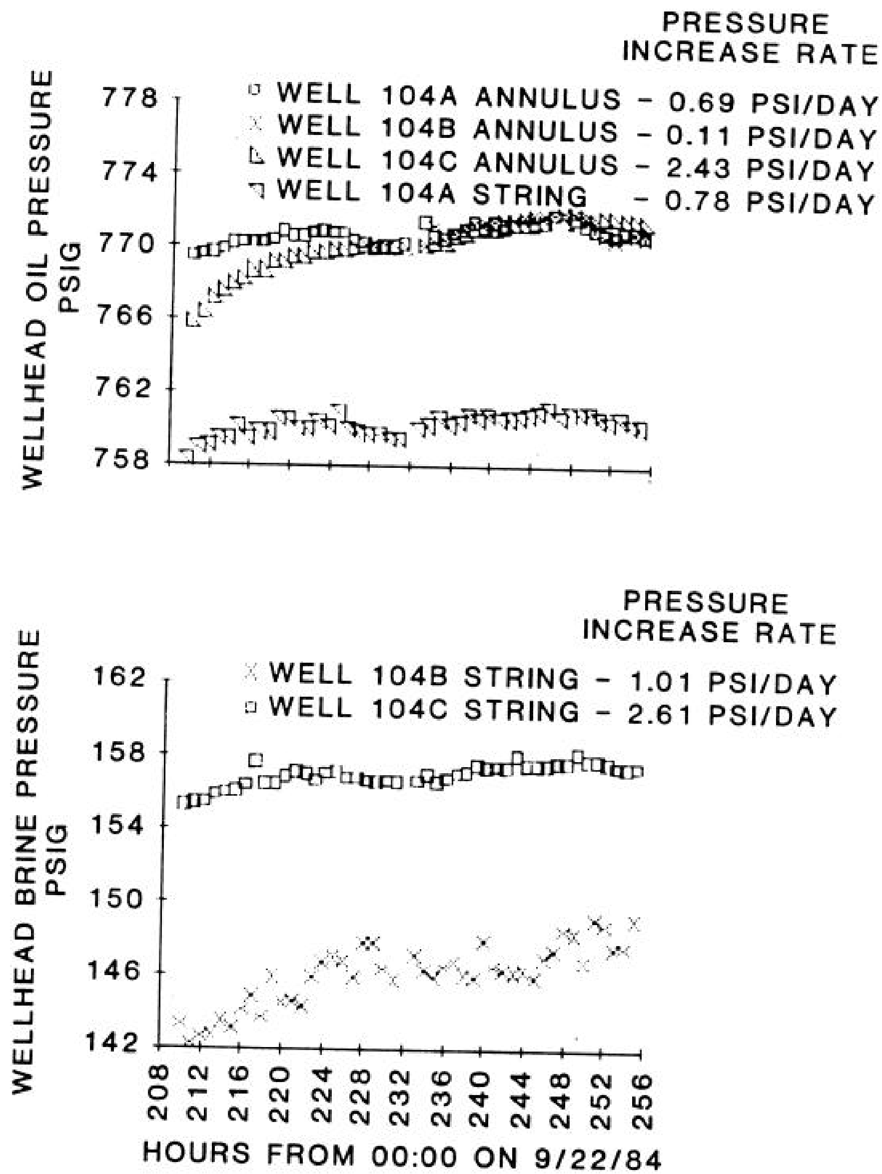
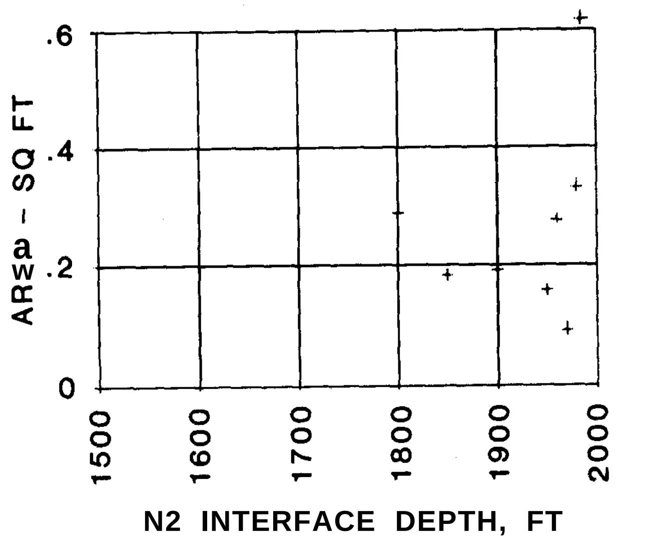
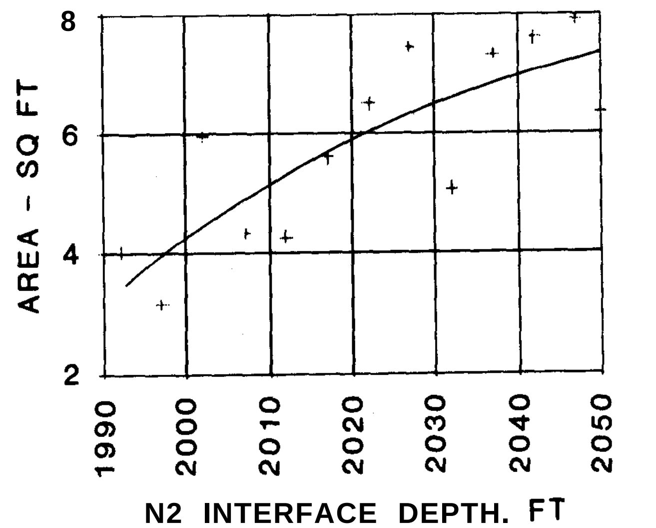


FIGURE 7. - EXPANDED SCALE PLOTS OF PRESSURE FOLLOWING SHUT IN AT MAXIMUM OPERATING PRESSURE.

FT	PSIG	LBS
1740	1328.3	0
1600	1333.4	136
1850	1347.6	97
1900	1363.1	105
1950	1374.9	85
1960	1378.12	8
1970	1381.7	15
1980	1384.7	32
1986	1385.5	30
1992	1388.2	190
1997	1389	123
2002	1390.9	232
2007	1392.3	170
2012	1393.5	167
2017	1395.3	220
2022	1397.2	255
2027	1398.6	290
2032	1400.2	201
2037	1401.4	286
2042	1403.3	300
2047	1405.2	313
2050	1405.8	149

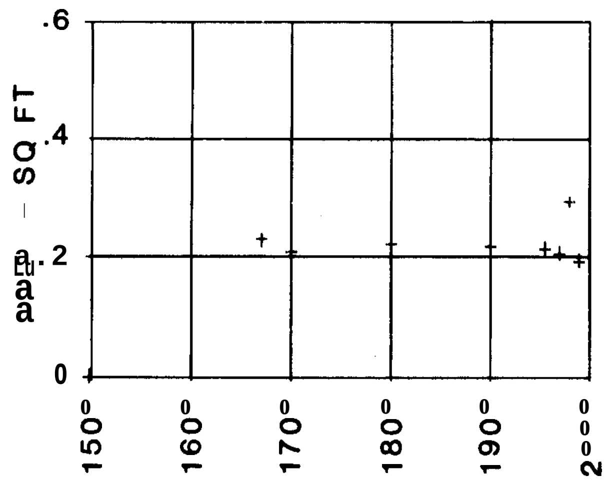


A. -CASED PART OF WELL, CROSS-SECTIONAL AREA 0.223 SQ FT



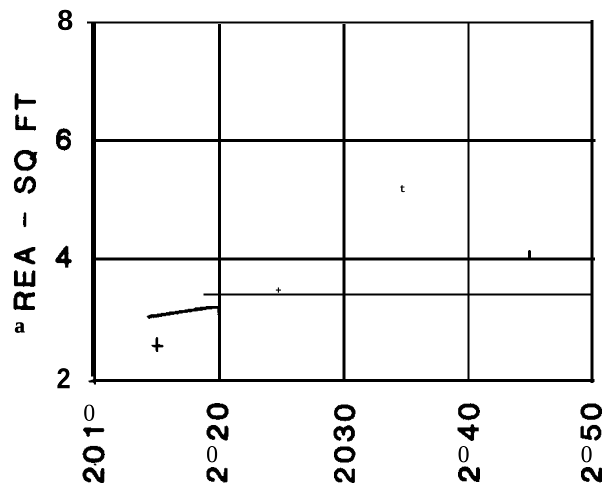
B. -OPEN HOLE BELOW CASING SEAT AT DEPTH OF 1987 FT

FIGURE 8. - CALIPER OF WELL BRYAN MOUND 104A USING MEASURED WEIGHT OF NITROGEN INJECTED. (ASSUMED NITROGEN COLUMN TEMPERATURE 100 DEG F, INCREMENTAL WEIGHT MEASUREMENT SCALE FACTOR OF 0.905 REQUIRED TO CALCULATE CORRECT CROSS-SECTIONAL AREA IN CASED PART OF WELL.)



A. -CASED PART OF WELL, CROSS-SECTIONAL AREA 0.223 SQ FT

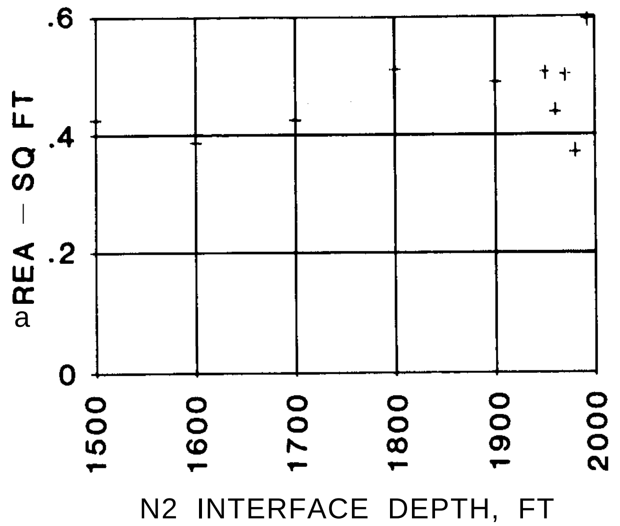
FT	PSIG	LBS
1497	1240.2	0
1670	1293.4	334
1700	1301.7	55
1800	1330.8	197
1900	1361.8	205
1955	1376.8	110
1970	1382.1	32
1980	1383.5	23
1990	1388.2	23
2012	1393.9	112
2015	1394.9	56
2020	1396.5	118
2025	1398:1	127
2030	1399.5	128
2035	1401.8	189
2040	1403.1	96
2045	1404.8	145
2050	1405.9	116



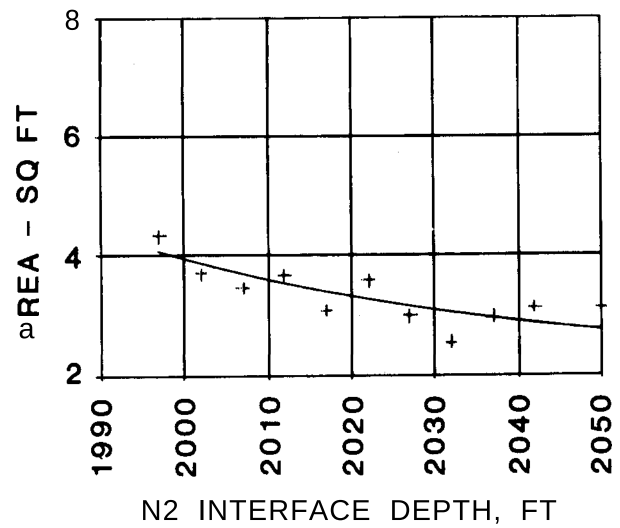
B. -OPEN HOLE BELOW CASING SEAT AT DEPTH OF 2010 FT

FIGURE 9. – CALIPER OF WELL BRYAN MOUND 1048 USING MEASURED WEIGHT OF NITROGEN INJECTED. (ASSUMED NITROGEN COLUMN TEMPERATURE 100 DEG F, INCREMENTAL WEIGHT MEASUREMENT SCALE FACTOR OF 1.000 REQUIRED TO CALCULATE CORRECT CROSS-SECTIONAL AREA IN CASED PART OF WELL.)

FT	PSIG	LBS
1246	1162.3	0
1500	1240.1	922
1600	1270.8	365
1700	1300.9	401
1600	1331.1	474
1900	1360.7	473
1950	1375.4	248
1960	1378.5	46
1970	1381.9	52
1980	1384.7	40
1992	1387.4	65
1997	1389	169
2002	1390.5	145
2007	1391.9	136
2012	1393.5	145
2017	1395.1	123
2022	1396.9	143
2027	1398.3	119
2032	1399.7	103
2037	1401.1	119
2042	1402.9	127
2050	1405.2	201



A. -CASED PART OF WELL, CROSS-SECTIONAL AREA 0.449 SQ FT



B. -OPEN HOLE BELOW CASING SEAT AT DEPTH OF 1992 FT

FIGURE 10. – CALIPER OF WELL BRYAN MOUND 104C USING MEASURED WEIGHT OF NITROGEN INJECTED. (ASSUMED NITROGEN COLUMN TEMPERATURE 100 DEG F, INCREMENTAL WEIGHT MEASUREMENT SCALE FACTOR OF 0.925 REQUIRED TO CALCULATE CORRECT CROSS-SECTIONAL AREA IN CASED PART OF WELL.)

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